MISSION DEFINITION AND REQUIREMENTS DOCUMENT

for the

Supernova / Acceleration Probe (SNAP)

University of California, Berkeley
Lawrence Berkeley National Laboratory

January 17, 2001
Draft 0.6

1.0 SNAP Mission Overview

Recent measurements carried out by the Supernova Cosmology Project (SCP) have made the startling discovery that the expansion of the universe is accelerating. This result is based on the Hubble diagram for Type Ia supernovae, and has been corroborated by results from several experiments, both similar and complementary. Einstein's General Theory of Relativity requires that some mechanism must drive this expansion rate either through a new form of energy, such as a new vacuum energy density (cosmological constant), or a yet unknown kind of particle or field fundamental to the creation and formation of the universe. The source of this acceleration is more powerful than the gravity from all seen and unseen forms of matter and known energy. Theorists are unable to explain the observed effect and so follow-up measurements would have a tremendous impact on the field of fundamental physics. The Supernova / Acceleration Probe (SNAP) Mission is expected to provide a understanding of the mechanism driving the acceleration of the universe. Over the mission lifetime, the satellite observatory is capable of measuring at least 2,000 distant Type Ia supernovae. These measurements will map out in detail the expansion rate of the universe at epochs varying from the present to 10 billion years in the past. SNAP will measure the key cosmological parameters Ω_m and Ω_Λ as well as determine the spatial curvature of the universe and thus provide a fundamental test of the theory of inflation – the theoretical mechanism that drove the initial formation of the universe. This sensitive experiment uses Type Ia supernovae as an astronomical standard candle to provide a distance scale, which, combined with the redshift obtained from the spectral lines from the supernova and its host galaxy, determine the cosmological parameters and ultimately the nature of the "missing energy" in the universe. Type II supernovae are also expected to provide an independent precision measurement of cosmological parameters from the near blackbody emission of the hot type II photosphere using a modified version of the Baade-Wesselink method to obtain a luminosity-distance scale.

The SNAP observatory will have an approximately 2 meter diameter rigid lightweight primary mirror with a focal plane covering one square degree. The optical imager will have approximately one billion CCD pixels, representing the largest imager ever fabricated. In order to facilitate thermal management of the observatory and instruments, and reduce light emissions from the earth's limb, the spacecraft is placed in high earth orbit above the radiation belts. Depending on orbit selection, possible orbit scenarios will require up to an aggregate ΔV 140 m/s burn from the spacecraft. SNAP would be launched from an Atlas II, Delta III, or Delta IV-M rocket. Our baseline science mission plan calls for continuous operation of SNAP for three years. This provides time to obtain initial photometric redshifts of target galaxies, monitor 2,000 distant Type Ia supernova, obtain final reference images and spectra, while interleaved with Type II supernova surveys and wide-field weak lensing surveys.

The Lawrence Berkeley National Laboratory and the University of California, Berkeley Space Sciences Laboratory are the lead institutions in collaboration with the science partners. Key funding for the mission is currently being sought from the U.S. Department of Energy (DOE) and the National Science Foundation (NSF). Both DOE and the NSF have played major roles in long-term funding for the Supernova Cosmology Project and participation from DOE and NSF in the satellite is a natural extension of the ongoing activities.

The SNAP mission is to be implemented under a "Principal Investigator Mode" (PI Mode) in order to reduce mission development times, costs, and schedules and achieve goals within the budget constraints. In the PI Mode, the PI takes full responsibility for all aspects of the mission, including instrument and spacecraft definition, development, integration, and testing, ground system operations, science operations, mission operations, and data acquisition and distribution with the intention of allowing the PI the maximum flexibility to conduct the investigation. The PI will establish and lead a mission team, optimizing the specialized talents of the various participating organizations. The PI will have the responsibility and accountability to accomplish the mission within the program's cost and schedule constraints. The mission team will use their own processes, procedures and methods to the fullest practical extent, and also develop new ways of doing business where cost, schedule and technical improvements can be achieved. Periodic progress reporting will combine cost, schedule and technical status using the team's own internal management reviews to meet the Government's reporting requirements.

The SNAP key personnel are Dr. Saul Perlmutter, SNAP PI and collaboration spokesperson, Dr. Michael Levi SNAP project director and co-PI, Prof. Robert Lin, Director, University of California Space Sciences Laboratory, and Peter Harvey also from the Space Sciences Laboratory as the SNAP Project Manager. They will be supported by experienced project management and systems engineering at the Space Science Laboratory and from Lawrence Berkeley National Laboratory.

2.0 Science Objectives

The SNAP baseline science objective is to obtain a high statistics calibrated dataset of Type Ia supernovae to redshifts of 1.7 with excellent control over systematic errors. The statistical sample is to be 2 orders of magnitude greater than the current published set of ~42 supernovae, and is to extend much farther in distance and time. From this dataset we expect to obtain a 2% measurement of the mass density of the universe, a 5% measurement of the vacuum energy density, a 5% measurement of the curvature, and a 5% measurement of the equation of state of the "dark energy" driving the acceleration of the universe. Systematic studies will include a measurement of the "reddening" of spectra from "ordinary dust" in the hosts galaxies of supernovae up to redshifts of 1.7, and detection of potential "grey dust" sources. Using Type Ia supernovae as standard candles will require measurement of the key luminosity indicators: the lightcurve peak and width. The redshift of the host galaxy of the supernova needs to be measured, supernova type identified, and spectral features studied. Effects correlated with host galaxy morphology and the position of the supernova in the host galaxy can also be studies due to the excellent resolution possible from space. These properties may indicate differences in stellar population from which the supernova came and therefore can be used to test whether the intrinsic brightness of the supernova changes systematically with redshift.

2.1 Baseline Science Mission

The SNAP baseline science mission assumes a 2.0 meter primary mirror with low obscuration and a large 1° x 1° field-of-view with diffraction-limited images. The baseline mission repeatedly samples approximately 20 fixed fields near the north and south ecliptic poles every four days searching for new supernova explosions. The discovered supernovae are then measured by photometry for the next four to eight months while the luminosity waxes and wanes. The selected observing fields minimize zodiacal light background and obscuration due to dust in our Galaxy. A medium-resolution spectrum is taken of each supernova at peak brightness. Beyond z = 1.2 a greatly limited sample of the discovered supernovae are followed as these can only be measured very slowly in the infrared. The satellite is expected to be able to follow up to 2,000 supernovae with redshifts ranging from 0.1 to 1.7.

The optics design for the SNAP satellite is expected to be a variant of a three-mirror telescope explored by M. Paul (M.Paul, Rev.Optics 14 p.169 1935; P.Robb Appl.Opt.17 p.2677 1978). The chief idea is to combine a concave primary paraboloid and a convex secondary paraboloid to approximate an afocal reducer, followed by a highly concave spherical tertiary. The secondary, located at the center of curvature of the tertiary, is then modified to eliminate the spherical aberation of the teriary. A 1.8 meter telescope of this type with a 1° field-of-view and a worst case 0.1 arcsec rms radius image was described in 1982 (R. Angel, Woolf & H. Epps, SPIE 332, p.134 1982; also J. McGraw, et al SPIE 331 p.137, 1982). In this design, the short focus of the tertiary places the detector buried deep within the secondary-tertiary space, making the detector inaccessible and blocking its own light and also needs a fairly large secondary 40% of primary size. Placing the tertiary significantly behind the primary was shown by Willstrop in 1984 to have significant advantages for wide-field imaging (Willstrop, R.V., MNRAS 210, 597-609, 1984). Finally, with the increased space between tertiary and primary a 45° optical flat can be inserted to fold the optical paths. A key to the success of the design is likely to be the feedback of a pointing error signal from the focal plane to the attitude control of a high stability spacecraft. Alternatively, is the inclusion of a tip-tilt element in the optical path to stabilize the image over the long, up to 4000 second exposures.

The size of the SNAP primary mirror has a dramatic effect on the science capabilities of the mission. The combination of the light gathering power of the mirror and the diffraction limit imposed by the aperture determine the number of supernovae that can be studied in a fixed interval, and varies as the *fourth power* of the aperture diameter. The requirement of diffraction limited optics at I-band has been selected to make best use of the capabilities of the photometric instruments and minimize exposure times. The wide-field optical photometry will also perform with the highest accuracy if the star images are properly sampled. A plate-scale of approximately 0.07 to 0.10 arcsec/pixel (depending on ongoing analyses) has been selected (assuming a 2 meter primary mirror diameter) as a best compromise between a wide field of view and achieving the best photometric accuracy. The mission is restricted to the minimum fairing dimensions of the Atlas II, Delta III, and the Delta IV-M composite fairing. Given the space required for spacecraft bus and telescope tube the aperture is not fixed by fairing diameter, rather by total length.

The largest aperture that is likely to fit is 2.4 meter. For apertures at 2.0m and below detector performance characteristics become critical. Furthermore, the aperture will be limited by manufacturing, cost, weight, and structural considerations. The baseline science mission for the observatory is summarized in Table 1.

Table 1. SNAP Observatory Requirements

Aperture	1.8 to 2.4 meter (2.0m nominal)
Field-of-view	Approximately 1° x 1°
Optical resolution	diffraction-limited at I-band
Wavelength coverage	350nm - 1700nm
Solar avoidance	70°
Temperature	Telescope 270 - 290 K (below thermal background)
Fields of study	North and South Ecliptic Caps
Pointing	Active Image Feedback
Plate Scale	0.07 to 0.12 arcsec/pixel for 2.0m aperture (0.10 nominal)

Photometry of Supernovae

The primary measurement of the mission is to obtain the peak brightness vs. redshift relationship of Type Ia supernovae out to a redshift of 1.7. These data will require taking accurate photometric observations of the supernova over the light-curve. An example of the restframe B-band light-curve is shown in Figure 1. It has been found experimentally that the supernova peak brightness can be standardized when viewed through a B-band filter where the B-band is defined in the *restframe* of the supernova (defined at rest with respect to the supernova). Therefore the photometry must seek to define an appropriate bandpass depending on the redshift of the supernova. The importance of this bandpass selection can be seen in Figure 2, where the B-band is superimposed over an example Type Ia supernova spectrum. The bandpasses can be defined either by having an extensive set of “redshifted B-band” filters, one for each small range of redshift, or by defining the bandpasses synthetically using spectrophotometry. Both are suitable and viable options. Given that a large field-of-view optical photometer is in the baseline for the mission, it may be possible to “batch process” large numbers of supernovae in a given observation so that the objectives can be met with a large number of filters. An example of a possible set of bandpasses with a average 25% non-overlap are given in table 2 below. A requirement for the number of filters has not yet been established.

Figure 1. B-band Light-curve for Type Ia Supernovae correct for redshift and lightcurve timescale.

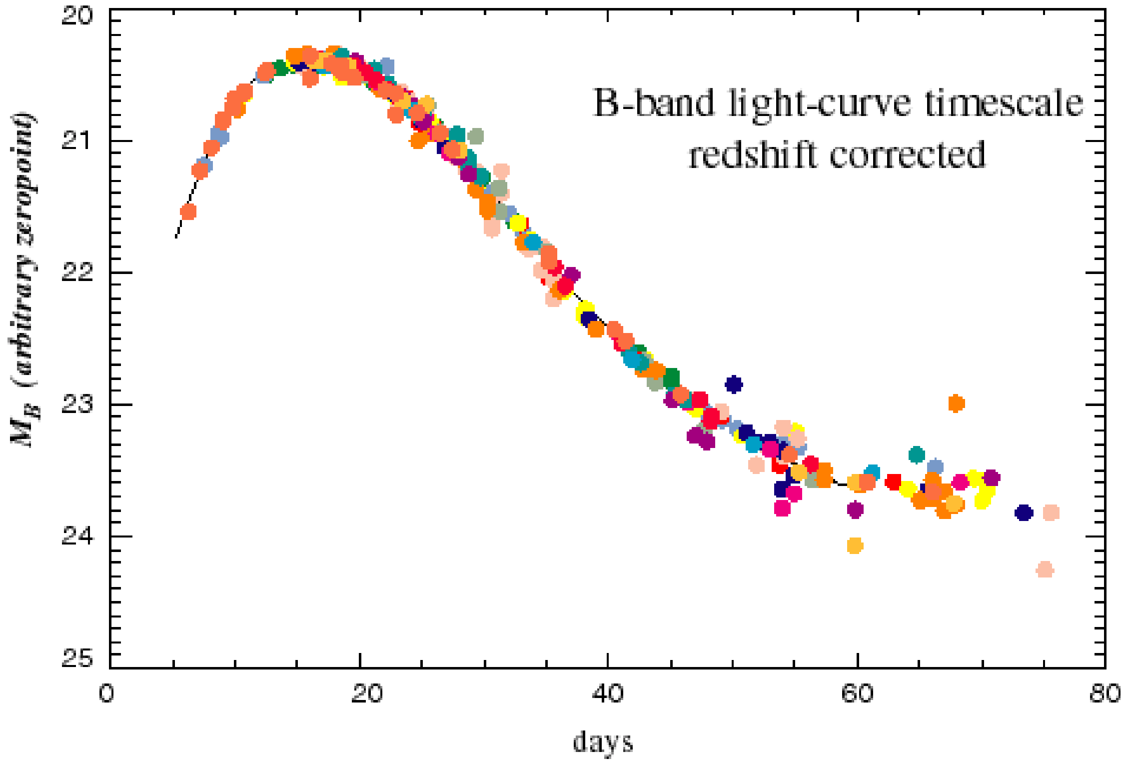

Figure 2. Example Type Ia supernova spectrum with B-band bandpass superimposed.

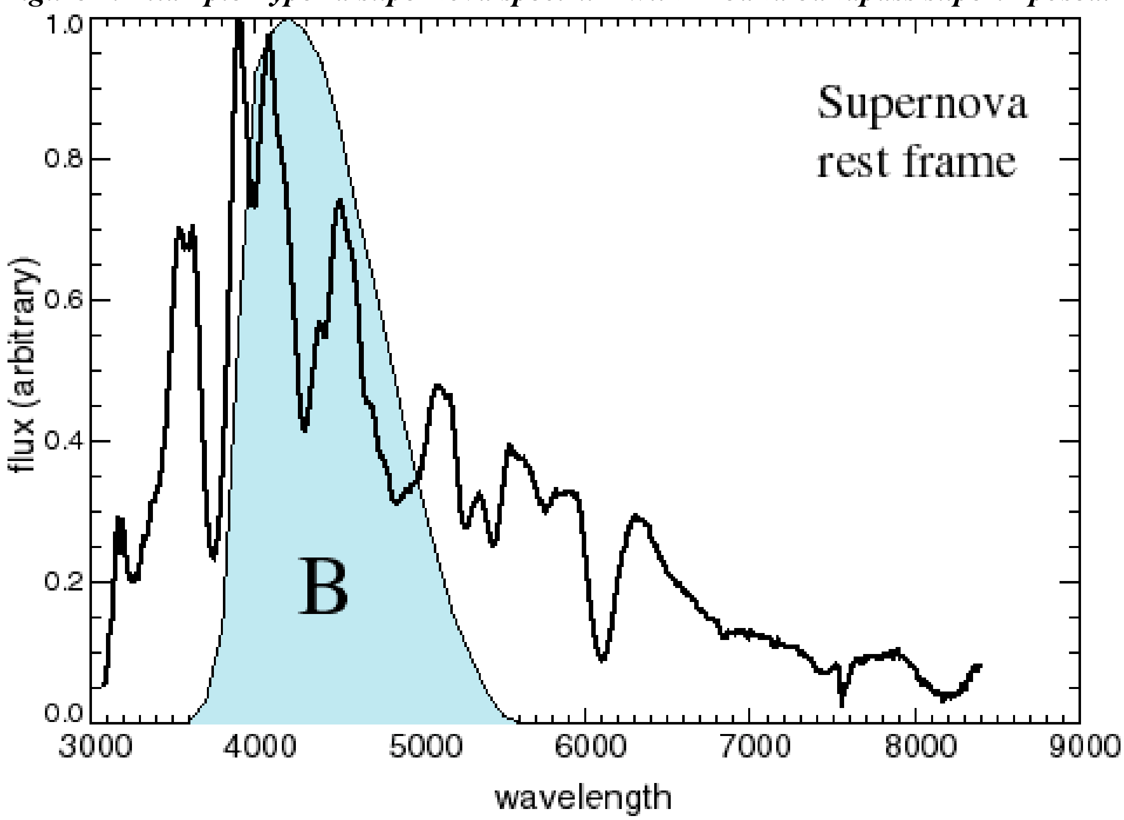

Table 2. Redshifted B-band filters

Effective redshift	B-band Center λ (μm)	B-band Bandpass $\delta\lambda$ (μm)
0	0.44	0.11
0.1	0.48	0.12
0.2	0.53	0.13
0.3	0.57	0.14
0.4	0.61	0.15
0.5	0.66	0.16
0.6	0.70	0.17
0.7	0.75	0.18
0.8	0.79	0.19
0.9	0.83	0.20
1.0	0.88	0.21
1.1	0.92	0.23
1.2	0.97	0.24
1.3	1.01	0.25
1.4	1.05	0.26
1.5	1.10	0.27
1.6	1.14	0.28
1.7	1.19	0.29

Instrumentation Requirements

The satellite is expected to carry three key instruments, a 1° x 1° wide field optical imager/photometer, a 350 nm – 1700nm spectrograph, and a small IR imager/photometer. The capabilities of these instruments must be a good match to the science requirements for the satellite. In particular, the instrumentation must provide all the elements of the supernova studies, namely: 1) early detection of supernovae, 2) B-band restframe photometry to follow the photometric lightcurve of the supernova as it waxes and wanes, 3) supernova color at peak and near peak brightness, 4) spectra at peak brightness to classsify the supernova and provide spectral diagnostics, 5) photometric redshifts of the host galaxies in advance of supernova follow-up, and 6) medium resolution spectra/photometry for a limited subset of supernovae sampled over the light-curve. Each of these elements can be expressed as a set of explicit requirements for the data products:

Detection. Early detection of Type Ia supernovae with S/N>7, would be obtained by comparing current images to a set of reference images. Early detection is required to measure the risetime in a model independent fashion within a few days of explosion and to allow identification well before peak brightness, approximately 3.8 magnitudes below peak. Twenty 1° x 1° fields would be repeatedly studied with a repetition rate of every four days for low redshift supernovae $z \leq 0.3$ with magnitude $m_{AB}(1.0\ \mu m) \leq 27$, every six days for supernovae $0.3 < z < 0.9$ with magnitude $m_{AB}(1.0\ \mu m) \leq 28$, and every eight days for $0.9 \leq z \leq 1.2$ with magnitude $m_{AB}(1.0\ \mu m) \leq 29$. Two 1° x 1° fields would be repeatedly studied with a repetition rate of every eight days for high redshift supernovae $1.2 \leq z \leq 1.7$ with magnitude $m_{AB}(1.0\ \mu m) \leq 30$. Only a sub-sample of the supernovae with $z > 1.2$ would be selected for further study. Note that the early discovery mitigates fast spacecraft scheduling.

Photometry. Photometric study of the supernova lightcurve by obtaining at least ten data points along the development of the lightcurve at fairly uniform intervals. Photometry for the supernova is obtained in the rest-frame B-band of the supernova using a filter set that approximates redshifted B-band filters. An overall fit to the lightcurve will require a stretch and extinction corrected peak brightness to an accuracy of 10%. To achieve this requirement data points would be taken at peak brightness (S/N>30), at 0.5 magnitude below peak (S/N>30) (two measurements at rise and fall of lightcurve), at 1.0 magnitude below peak (S/N>20), at 1.5 and 2.0 magnitude below peak (S/N>15), and at 2.5 magnitude below peak on trailing edge of lightcurve (S/N>10) except in the IR channel and detector dependent. V-band photometry is obtained at either by light-curve fit as described for B-band, or by single point peak measurement (S/N>50). Restframe photometry in B-band is redshifted into the observer frame by $(1+z)$. Photometry can be obtained by multiple fixed filters, an integral field spectrograph which preserves photometry, or other low resolution spectrograph provided there are no photometric losses. An optimal redshifted B-band filter or synthesized filters applied to spectrophotometry would eliminate a principal source of systematic error from the k-corrections. The photometry will require both optical and NIR coverage. Optical photometry, IR photometry, and spectrophotometry are expected to be performed with a systematic accuracy of 1% over the redshift $0.3 < z < 1.7$.

Spectra: In order to classify the supernova as Type Ia a spectrum is obtained at peak magnitude. The defining signature of a Type Ia supernova is the SiII feature at 6250A. Spectral luminosity indicators include the SiII features and the CaII features near 3950A, the observing time requirements are based on the CaII features for simplicity. In the optical channel, for supernovae with redshift $0.02 \leq z \leq 0.4$ the labframe sampling required is 15 Angstroms (S/N>10) to study wavelengths between 3500-4800A in the restframe of the supernova. For supernovae with redshift $0.5 < z < 1.0$ the labframe sampling required is 30 Angstroms (S/N>10) to study wavelengths between 3500-4800A in the restframe of the supernova. For supernovae with redshift $1.0 \leq z \leq 1.5$ the labframe sampling required is 60 Angstroms (S/N>14) to study wavelengths between 3500-4200A in the restframe of the supernova. A single medium resolution optical spectrograph extending from 3500A to 10000A would appear to be sufficient to satisfy these CaII requirements; for z>0.6 the SiII features are studied with a NIR spectrograph. For the highest redshift supernovae z>1.5, a NIR channel would also permit study of the CaII spectral features. In the NIR arm, for supernovae with redshift $1.5 \leq z \leq 1.7$ the labframe sampling required is 100 Angstroms (S/N>20) to study wavelengths between 3800-4200A (CaII) in the restframe of the supernova. In order to classify supernova z>0.6 and study the SiII spectral features using the SiII (6250A) feature the NIR arm will require finer samplings of 30A, and 60A. For clean classification and spectral diagnostics it is required that a host galaxy spectrum be obtained and subtracted from the supernova spectrum.

Color. To correct the supernova data for extinction from host galaxy dust restframe V-band photometric point is obtained at peak brightness to S/N>50 band for all supernovae in the sample. Additional filter bands and near peak measurements (1 magnitude below peak) would be desirable.

Redshift. Obtain pre-explosion host galaxy redshift estimate based on photometric redshifts (only once per field) based on images in multiple filters to S/N>30. Obtain accurate host galaxy red-shift from at-peak supernova spectrum or final reference spectrum; this requires access to redshifted H-alpha or 4000A break. These features are close to the key supernova features (CaII, SiII), so the requirements for the suprenova optical and NIR spectroscopy are sufficient.

Medium Resolution IR spectra (evolution). On a 10% subset of the data obtain a medium-resolution spectrum at peak brightness (S/N>30 per 15A) for z<1.0 to check for evolution of spectral features. Wavelength range is from 3000A to 6500A in the restframe of the supernova. For $z > 0.5$, this will require good near-IR spectroscopy.

Host galaxy spectroscopy: Obtain host-galaxy final reference spectrum, and measure redshift from at-peak supernova spectrum and/or final reference spectrum. The IFU spectrograph will sample host-galaxy light underneath and around the SN spectrum obtained at peak. This light must be subtracted, and in many cases this will require a final reference spectrum of the host-galaxy after the SN has faded. Individually or in combination these spectroscopic observations will be used to measure the host galaxy redshift when possible. Strong galaxy spectral features are H-alpha (6567A) and NII (6587A) for star-forming galaxies, and the spectral break at 4000A for quiescent galaxies. These spectral features are near in wavelength to key Type Ia supernova spectral features (SiII and CaII, respectively), and therefore do not impose additional requirements on the spectral coverage. Host galaxy spectroscopy benefits from the ability of the IFU to collect light over all or most of the face of the (resolved) galaxy. Host galaxy spectroscopy will benefit from the lowest possible readnoise and dark current from the spectrograph detectors.

Optical Photometry

The requirement for supernova detection and photometry is fulfilled by a large field imager based on CCD technology. The pixel size is chosen to be as low as attainable in science grade imagers to minimize the overall size of the device. The high-resistivity p-channel CCD technology provides high quantum efficiency at 1000 nm since the fully-depleted devices are 300 μm thick and back-illuminated. The shortest exposure time is 100 sec while the longest single exposure is set by cosmic ray contamination, at 1000 sec. Multiple frames, would be stacked and cleaned of cosmic rays during ground processing. The longest aggregated image (summed from many exposures) in the imager is one hour. For the parameters given in Table 3, which assumes a 2 meter primary mirror and an overall system detection efficiency of 60%, the imager sensitivity is limited only by zodiacal light background.

Table 3. Optical Imager/Photometer Requirements

Field-of-view	Approximately 1° x 1°
Plate Scale	0.07 to 0.10 arcsec/pixel (0.10 nominal)
Wavelength coverage	350nm - 1000nm
Detector Type	High-Resistivity P-channel CCD's
Detector Architecture	2k x 2k, 12 or 10.5 micron pixel
Detector Array Temperature	135 - 150 K
Detector Quantum Efficiency:	65% @ 1000nm, 92% @ 900nm, >85% @ 400-800nm
Photometric Accuracy	1% relative
Read Noise	4 e- @100kHz
Exposure Time	100 sec to 1000 sec (single exposures)
Dark Current	0.08 e-/min/pixel
Readout Time	20 sec
Limiting Magnitude Sensitivity	30th magnitude in I-band
Exposure control	Mechanical shutter
Filter Wheel	15 bands (U, V, R, I, Z, & 10 special filters)

The optical photometer will be fabricated by LBNL & UCB using a new state-of-the-art CCD based on ultra-high purity high-resistivity n-type silicon. These CCD's are fully-depleted and back-illuminated with superior response. The largest devices currently in operation at Lick Observatory are 2k x 2k with 15 μm^2 pixels. Larger 2k x 4k devices are currently in fabrication as well as devices with 12.0 and 10.5 μm^2 pixels. The technology has also been moved to a commercial foundry with the first 6" wafer lot currently in manufacture. Since the devices do not require thinning to obtain high sensitivity with back-illumination the devices are extremely robust and easy to fabricate in volume. Early measurements at the LBNL 88" cyclotron also indicate enhanced radiation tolerance. Additional studies will be required to validate the devices for the SNAP mission. Further information about this technology can be found at URL, http://ccd.lbl.gov. LBNL has a long history in the fabrication of very large silicon array detectors, the largest contains one-square meter of silicon detectors. A larger instrument, of forty square meters of silicon detector is currently in fabrication.

Given the very large number of devices in the optical photometer, LBNL and IN2P3/France have also begun development of radiation hard multi-channel preamplifier/correlated double samplers developed on an integrated circuit. Appropriate radiation hard 16-bit analog-to-digital converters are currently under investigation. These IC's would be fabricated in a radiation hard process.

Detection of supernovae is accomplished by a repeated comparison of fixed fields to reference images. The imager would obtain twenty discovery fields from dark regions around the north and south ecliptic poles. These discovery fields would have a limiting detection magnitude (S/N>7) of $m_{AB}(1\ \mu m) < 27$ recorded at four day intervals, $m_{AB}(1\ \mu m) < 28$ recorded at six day intervals, and $m_{AB}(1\ \mu m) < 29$ recorded at eight day intervals. Two of these fields would have a limiting detection magnitude (S/N>7) of $m_{AB}(1\ \mu m) < 30$ taken every eight days. This strategy is summarized in Table 4. This data would be obtained concurrently with the optical photometry, discussed next, and so would not require additional mission observation time with the exception of the 2 deep fields. The average data transmission requirement from all optical photometric images assuming 50% loss-free compression is 50 Mbit/s, these images represent the majority of the data to be transmitted. Lossy data compression techniques, discussed below, could provide significant further reduction in the data to be transmitted.

Table 4. Discovery Fields

Peak AB mag. B-band restframe	*Peak SNe flux [e-/s]*	*Zodiacal [e-/s]*	*Total Time per field [hrs]*	*Filter*	*Fields*	*Repeat Interval [days]*
27	0.40	0.17	0.22	I-band	20	4
28	0.16	0.17	0.54	Z-band	20	6
29	0.06	0.17	2.95	Z-band	20	8
30	0.03	0.17	12.59	Z-band	2	8

The follow-up optical photometry is obtained without specific knowledge of the location of new supernovae. The optical photometer obtains wide-field frames overlapping the positions of the discovery frames. Some of the photometry frames may be taken while the satellite is taking spectra of specific supernovae. The photometer obtains frames in each of a specified list of redshifted B-band filters with exposures of sufficient duration to obtain all the data points required to reconstruct the lightcurve. The longest optical photometric exposure is approximately one hour. The photometry is also obtained at regular intervals in order to obtain data points that reasonably approximate the required ten photometric points along the lightcurve. As shown in Table 5, the B-band photometry is divided into ranges of redshift for photometry in a specific filter. Given the correlation between brightness and redshift the exposure times are known a priori. The parameters given in Tables 4 & 5 assume a 2 meter primary mirror and an overall optical system detection efficiency of 60% including telescope obscuration, reflectance, optical transport, and detector quantum efficiency.

Table 5. Optical Photometry

Redshi	*SNe Rate yr/1°*	*Peak AB mag. B-band restframe*	*Peak Sne flux [e-/s]*	*Peak Zodiacal [e-/s]*	*Longest Expose [hrs]*	*B-band Filter Center [μm]*	*Field:*	*# SNe follow*	*Repeat Time [days]*	*Total Time [days]*
0.1	0.7	19.00	634.05	0.10	0.11	0.48	20	14	4	8.4
0.2	2.2	20.60	145.25	0.12	0.11	0.53	20	44	4	8.4
0.3	4.1	21.60	57.83	0.13	0.11	0.57	20	82	4	8.4
0.4	6.2	22.33	29.52	0.14	0.11	0.61	20	124	6	5.6
0.5	8.1	22.91	17.30	0.15	0.11	0.66	20	162	6	5.6
0.6	9.8	23.39	11.12	0.16	0.22	0.70	20	196	6	11.3
0.7	11.3	23.80	7.62	0.16	0.22	0.75	20	226	6	11.3
0.8	12.5	24.16	5.47	0.17	0.23	0.79	20	250	6	11.6
0.9	13.5	24.47	4.11	0.17	0.36	0.83	20	270	8	13.8
1	14.3	24.76	3.15	0.17	0.58	0.88	20	286	8	22.0
1.1	14.9	25.02	2.48	0.17	0.89	0.92	20	298	8	33.7
1.2	15.2	25.25	2.01	0.17	1.35	0.97	20	304	8	51.5
total								2256		191.9

Modern X-band transmission schemes appear to be able to transport the full 50 Mb/s data payload. Analysis of deep HST images indicates that selecting only regions around known galaxies or identified supernova candidates would provide a ten-fold reduction in the data. Other compression techniques, such as wavelet compression preserve photometric information and have been shown to also provide a ten-fold reduction in the data. Some of these techniques would require flattened and bias subtracted data to be computed aboard the spacecraft.

IR Photometry

The IR photometer is constructed from one or more small HgCdTe devices with a 1.7 μm wavelength cut-off. This cut-off is a good match to the approximately room temperature operating point of the optical surfaces of the telescope. The requirements for the IR photometer are shown in Table 6. The devices could have a fixed filter on each device, or a single device with a filter wheel. Using fixed filters may permit the placement of the HgCdTe devices within the focal plane of the optical photometer. The follow-up IR photometry will require specific knowledge of the location of each new supernova (approximately one week after discovery). The IR photometer obtains small frames determined by pointing the satellite at the supernova. Other options for the IR photometer are discussed in the "enhanced science mission" section.

The IR photometer would be unable to follow all supernovae seen in each of the most distant discovery frames. Consequently a subset would be selected for follow-up. As shown in Table 7, the longest photometric IR observation is 7 hours and would require a total of 31 hours of observing time to follow the complete light curve of a z = 1.7 supernova out to a limiting magnitude of $m_{AB}(1\mu m) < 28.2$. Following the supernova lightcurve in the infrared will require the highest possible throughput and quantum efficiency. The parameters given in Table 6 assume a 2 meter primary mirror and an overall IR system detection efficiency of 45% including telescope obscuration, reflectance, optical transport, and detector quantum efficiency. With these parameters the IR photometer is only limited by zodiacal light background. HgCdTe arrays are known to have strong intrapixel sensitivity variations. Therefore, a careful study of the appropriate scale and dithering pattern will be undertaken to ensure that the IR photometer will produce accurate, unbiased photometry. The data transmission requirement for the IR photometry data is negligible.

The highest redshift supernova followed photometrically by the optical photometer will require measurement of the V-band restframe color of the supernova at peak magnitude using the IR photometer since the light will be redshifted into the infrared. Since these measurements are only performed at peak brightness the limiting magnitude for the measurements is $m_{AB}(1\mu m) < 25.2$, as shown in Table 8, and very little time is devoted to these measurements. It maybe necessary to assign additional observing time to obtain color at additional epochs near maximum brightness. The data transmission requirement for the IR V-band photometry data is negligible.

Table 6. IR Imager/Photometer Requirements

Field-of-view	1.4 to 2.0 arcmin on a side
Plate Scale	0.08 – 0.12 arcsec/pixel (0.12 nominal)
Pixelization	1K x 1K
Wavelength coverage	1000nm - 1700nm
Location	TBD
Detector Type	HgCdTe (1.7 μm cut-off)
Detector Architecture	WFPC3
Detector Array Temperature	120K – 140K (to achieve dark current)
Detector Quantum Efficiency	70% average
Photometric Accuracy	1% relative
Read Noise	5 e- (multiple samples)
Dark Current	3 e-/min/pixel
Limiting Magnitude Sensitivity	28.5th magnitude (AB)
Exposure control	Mechanical or electrical shutter
Filters	J&H, plus five special filters

Table 7. IR Photometry

Redshift	*# SNe follow*	*Peak AB mag. B-band (restframe)*	*Peak SNe flux [e-/s]*	*Zodiacal [e-/s]*	*Longest Expose [hrs]*	*Time per Lightcurve [hrs]*	*B-band Filter Center [μm]*	*Fields*	*Total Time [days]*
1.3	30	25.47	1.23	0.18	2.2	9.8	0.95	2	12.2
1.4	30	25.67	1.02	0.17	3.0	13.2	1.01	2	16.6
1.5	22	25.85	0.87	0.17	4.0	17.6	1.07	2	16.2
1.6	16	26.03	0.73	0.17	5.5	23.6	1.13	2	15.8
1.7	12	26.19	0.63	0.17	7.2	30.8	1.20	2	15.4
total	110								76.1

Table 8. IR V-band Photometry

Redshift	*Sne Rate yr/1°*	*Peak AB mag. B-band (restframe)*	*Peak Sne flux [e-/s]*	*Zodiacal [e-/s]*	*Time per Sne [hrs]*	*Fields*	*# Sne follow*	*Total Time [days]*
0.9	13.5	24.47	3.08	0.18	0.33	20	270	3.7
1	14.3	24.76	2.36	0.18	0.45	20	286	5.4
1.1	14.9	25.02	1.86	0.18	0.60	20	298	7.4
1.2	15.2	25.25	1.50	0.18	0.81	20	304	10.2
1.3	15.4	25.47	1.23	0.18	1.11	2	30	1.4
1.4	15.5	25.67	1.02	0.17	1.34	2	30	1.7
1.5	15.4	25.85	0.87	0.17	1.72	2	22	1.6
1.6	15.3	26.03	0.73	0.17	2.20	2	16	1.5
1.7	15.1	26.19	0.63	0.17	2.77	2	12	1.4
total							1268	34.3

Optical and IR Spectroscopy

The architecture of both the optical and IR spectrograph is based on an integral field spectrograph with an image slicer. The image slicer eliminates the need for a slit and greatly reduces the pointing accuracy required to place the supernova within the field of view of the spectrograph while preserving photometric accuracy because of the 100% filling factor. The optical spectrograph may require selectable resolution (or binning) in order to achieve an optimum of performance and exposure times. Furthermore, the spectral features of the high redshift supernovae are dilated by 1+*z*, so that reduced resolution is a good match to standardizing the performance over all supernovae followed. The performance features of the optical and IR spectrograph arms are shown in Tables 9 and 10, respectively. The optical and IR spectrograph is assumed to have multiple arms, either as a single instrument, or as two instruments with overlapping wavebands. The cross-over wavelength between the arms would be determined by the availability of high throughput dichroics. It would be considered highly advantageous to be able to operate the longer wavelength arm of the optical spectrograph simultaneously with the IR spectrograph.

The optical and IR spectroscopy is obtained by pointing the satellite at each individual supernova one at a time during its peak brightness. The optical resolution ranges from 15A to 60A for the most distant supernovae in the study. The parameters given in Tables 11 and 12 assume a 2 meter primary mirror and an overall optical system efficiency of 45% and an IR system efficiency of 35% including telescope obscuration, reflectance, optical transport, and detector quantum efficiency.

Table 9. Optical Spectrograph Arm Requirements

Spectrograph architecture	Integral field spectrograph, two arms
Wavelength coverage	350-600 nm, 600-1000nm
Plate scale	0.07 – 0.1 arcsec/pixel (0.07 nominal)
Spatial resolution of image slicer	0.07 – 0.15 arcsec (0.07 nominal)
Field-of-View	Determined by pointing accuracy of spacecraft
Location	TBD
Photometric Accuracy	1% relative
Resolution	15A, 30A, 60A selectable
Detector Type	High-Resistivity P-channel CCD’s (TBD)
Detector Architecture	1k x 1k, 12 micron pixel (TBD)
Detector Array Temperature	135-150 K
Detector Quantum Efficiency:	65% @ 1000nm, 92% @ 900nm, >85% @ 400-800nm
Photometric Accuracy	1% relative
Read Noise	2 e-
Dark Current	0.08 e-/min/pixel
Readout Time	20 sec or longer to optimize readout nose
Exposure control	Mechanical or electrical shutter (TBD)

Table 10. IR Spectrograph Arm Requirements

Spectrograph architecture	Integral field spectrograph
Wavelength coverage	1000-1700 nm
Plate scale	0.07 – 0.12 arcsec/pixel (0.12 nominal)
Spatial resolution of image slicer	0.07 – 0.15 arcsec (0.12 nominal)
Field-of-View	Determined by pointing accuracy of spacecraft
Location	TBD
Resolution	50A, 100A selectable (TBD)
Detector Type	HgCdTe
Detector Architecture	1k x 1k, 18.5 micron pixel
Detector Array Temperature	120K – 140K (to achieve dark current)
Detector Quantum Efficiency:	70% average
Photometric Accuracy	1% relative
Read Noise	< 4 e- (multiple samples)
Dark Current	< 1 e-/min/pixel
Readout Time	20 sec
Exposure control	Mechanical or electrical shutter (TBD)

Table 11. Optical Spectroscopy

Redshift	*# SNe follow*	*Lab Resolution [Angstroms]*	*Peak SNe Flux [e-/s]*	*Zodiacal [e-/s]*	*Galaxy [e-/s]*	*Time per SNe [hrs]*	*Total Time for Spectra [days]*
0.1	14	15	6.04	0.0005	0.0015	0.11	0.1
0.2	44	15	1.27	0.0005	0.0011	0.11	0.2
0.3	82	15	0.47	0.0005	0.0008	0.11	0.4
0.4	124	15	0.22	0.0005	0.0006	0.14	0.7
0.5	162	30	0.24	0.0010	0.0009	0.23	1.6
0.6	196	30	0.15	0.0010	0.0007	0.35	2.8
0.7	226	30	0.09	0.0010	0.0005	0.59	5.6
0.8	250	30	0.06	0.0009	0.0004	0.84	8.7
0.9	270	30	0.05	0.0009	0.0003	1.08	12.1
1.0	286	60	0.07	0.0017	0.0006	1.26	15.1
1.1	298	60	0.05	0.0016	0.0005	1.69	21.0
1.2	304	60	0.04	0.0016	0.0004	2.31	29.2
total	2256						97.6

Table 12. IR Spectroscopy

Redshift	*# SNe follow*	*Lab Resolution [Angstroms]*	*Peak SNe Flux [e-/s]*	*Zodiacal [e-/s]*	*Galaxy [e-/s]*	*Time per SNe [hrs]*	*Total Time for Peak Spectra [days]*
1.3	30	100	0.039	0.0056	0.0012	8.1	10.2
1.4	30	100	0.031	0.0053	0.0010	11.6	14.5
1.5	22	100	0.025	0.0050	0.0009	16.0	14.7
1.6	16	100	0.020	0.0047	0.0008	22.3	14.8
1.7	12	100	0.017	0.0045	0.0006	30.0	15.0
total	110						69.1

Summary Rates

In seventeen months of study, as shown in Table 13, the satellite can discover, follow the lightcurve, and obtain spectra at peak brightness for 2366 supernovae. Most of these supernovae are obtained in the critical region of $0.5 < z < 1.2$ where the experiment has peak sensitivity to the value of the cosmological constant. The time for the color observations are only shown for redshifts between 0.9 and 1.2 where there is no multiplex advantage (see Table 8).

Table 13. Summary

Redshift	# Sne follow	Fields	Detection [days]	Photometry [days]	Spectroscopy [days]	Color[days]
0.1	14	20		8.4	0.1	parasitic
0.2	44	20		8.4	0.2	
0.3	82	20		8.4	0.4	
0.4	124	20		5.6	0.7	
0.5	162	20		5.6	1.6	
0.6	196	20		11.3	2.8	
0.7	226	20		11.3	5.6	
0.8	250	20		11.6	8.7	
0.9	270	20		13.8	12.1	3.7
1.0	286	20		22.0	15.1	5.4
1.1	298	20		33.7	21.0	7.4
1.2	304	20	parasitic	51.5	29.2	10.2
1.3	30	2		12.2	10.2	1.4
1.4	30	2		16.6	14.5	1.7
1.5	22	2		16.2	14.7	1.6
1.6	16	2		15.8	14.8	1.5
1.7	12	2	48	15.4	15.0	1.4
total	2366		48	268	167	34

2.2 Minimum Science Mission

The SNAP Minimum Science Mission reduces the telescope aperture to 1.8 meters. This will reduce the number of supernovae that can be measured in one year by approximately 30-40%; this will also negatively impact the number of the highest redshift supernovae that can be followed, especially for z>1.5. This will additionally negatively impact the requirements for and availability of the scientific imagers (e.g. detector read noise). A factor two smaller optical imager is also to be considered. These reductions in scope may be separately considered.

2.3 Enhanced Science Mission

The SNAP Enhanced Science Mission increases the telescope aperture up to as much as 2.4 meters. This will greatly increase the number of supernovae that can be followed in one year at the highest redshifts. The number of pixels in the optical imager would actually decrease since the mission goals would be more quickly satisfied thereby reducing the required field-of-view. The IR photometer would have greatly enhanced capabilities including full multiplexing. This could permit batch-mode IR photometric observations to be made simultaneously with the optical photometric observations, thereby eliminating separately scheduled IR photometry observations. These enhancements may be separately considered.

2.4 Science Data Products

In a NASA sponsored project, open access to scientific data is regulated by the National Aeronautics and Space Act. In a DOE/NSF project, project management has greater freedom to regulate data access to maximize benefit to the collaboration, scientific community, and public. Data used in the preparation of a graduate student thesis is an excellent example where some regulation can be used for great overall benefit. Although there *can be* limited proprietary science data rights in a DOE/NSF experiment, the majority of the SNAP archival data will be made available to the public and the science community within a reasonable period of time, likely one year from final reference images. The deep-field co-added images would be made available even sooner. Data release will include making data available on-line at the DOE National Energy Research Scientific Computing Center located at LBNL. Data archiving and distribution will be available through the Mission Operations Center and/or through other NSF centers. Additionally, we expect to be able to provide a significant and ever increasing fraction of the SNAP observing time in a restricted mode to meritorious survey programs.

2.5 Education and Public Outreach

SNAP will have a significant education and public outreach program. The program will make use of the intense public interest in the accelerating universe as a unique opportunity to engage students, educators, and the general public in an enhanced understanding of our physical world. The program will have two important goals: 1) addressing traditional education and public outreach audiences: grades K-14 students and teachers, and the general public; and 2) upper-level undergraduates and graduate students pursuing advanced degrees in the sciences and engineering disciplines.

2.6 Spacecraft

In Table 14, the critical specifications for the SNAP spacecraft are given. Many of these requirements are still under development to allow design trade-off flexibility.

Table 14. Spacecraft Requirements

Launch Vehicle	Delta IV-M, maximum lift to lunar assist orbit 2700 kg
Mission Operation	3 years
Orbit	HEO (8 Re x 57 Re)
Telemetry	50 Mbit/s data (average)
Spacecraft attitude control	3-axis stabilized, low jitter
Pointing jitter z axis (rotation)	< 50 microradians/exposure (3 sigma) (1 µrad = 0.2 arcsec)
Pointing jitter x-y axis	Focal plane stabilized by 2-axis tip-tilt mirror to 0.03 arcsec/exposure (3 sigma), or by ACS using focal plane feedback
Exposure time	Maximum single exposure 4000 sec.
Pointing accuracy (instrument)	Place supernova within bore of spectrograph
Pointing knowledge (instrument)	Place supernova within bore of spectrograph
Acquisition time new field	5 minutes (for adjacent fields)
Observing Duty-Factor	80%
Maximum Total Mass	1800 kg (wet)
Maximum Spacecraft Mass	500 kg (wet)
Maximum Payload Mass	1300 kg
Maximum Peak Payload Power	600W, 10% duty cycle
Average Payload Power	300W
Peak data rate to storage	1 billion pixel frame in 20s readout
Maximum data xmit lag time	1 day
Solid State Recorder Capacity	Store multiple ~25 Gbyte compressed images
Propulsion system	for attitude control and up to 140 m/s orbit insertion
Thermal control	telescope < 294K, focal plane array ≤150K, IR ≤130K
Solar Avoidance	70 degrees
Field of View	nominally centered near north and south ecliptic poles
Thermal management	passive coatings, thermal insulation, heaters, radiators
Redundant architecture	Failure mitigation & identification of critical components
Compatibility with telescope	Maximize flexibility and volume for telescope & instruments
Primary to secondary mirror	Approx. 2.1 meter
Secondary to tertiary mirror	Approx. 1.5 meter
Link assumptions	Prefer use of SSL ground station, 2^{nd} potentially in southern hemisphere
Telemetry	25W output RF X-band

3.0 Mission and Project Requirements

3.1 Mission Organization

The SNAP mission cost is expected to be shared with major contributions from the U.S. Department of Energy, the National Science Foundation, and major foreign institutions. Responsibility for managing the SNAP project for the U.S. Government is that of the Principal Investigator and his/her management team. Disbursement of all SNAP mission funds will be subject to the concurrence of the SNAP Principal Investigator. Reductions in the proposed scope must be approved by the SNAP Principal Investigator and with concurrence of DOE and NSF. Other adjustments may be made within the mission, as required. Management of the project is described elsewhere.

3.2 Schedule Milestones and Reviews

Reporting requirements and reviews will be consistent with ensuring that DOE and NSF maintain an effective understanding of the progress of the development and execution of the mission. To this end reports and supporting materials will be based on internal mission team products and processes to the maximum extent practical and in accordance with DOE order 413.

DOE and NSF will evaluate the SNAP mission periodically to assess the progress of the mission and its readiness to proceed to the next phase. This evaluation will assess technical, management, cost and schedule progress to verify that the project can be completed in accordance with the mission requirements within the cost and schedule commitments.

3.3 Management System

The SNAP mission will establish an effective and efficient management system which will assure that the science objectives can be accomplished within the schedule and cost limitations. As a minimum, the following management requirements shall be met:

3.3.1 Scheduling

A fully integrated scheduling system shall be established and implemented to manage all mission elements through all phases of the SNAP mission. This system will include the development of network schedules and identification of critical paths and schedule slack. A set of performance metrics to measure mission progress will also be developed. These metrics shall be compatible with the mission scheduling and cost control/reporting systems.

3.3.2 Key Personnel

The key personnel including the Principal Investigator, the Project Director, and the Project Manager, must be approved by DOE and NSF. There will also be assigned subsystem and instrument managers.

3.3.3 Contract Deliverables

Major contracts which are developed as part of the mission will be subject to review by the Principal Investigator and his/her management team in assuring adherence to the Baseline Mission Concept, control of costs, and maximizing the science return of the mission. Contract deliverables from the research teams, collaborating institutions, and from industrial partners, will be subject to review by the Principal Investigator and his/her management team.

4.0 Mission Responsibilities

Mission responsibilities have not been specifically established; however, we indicate those areas that have some greater certainty below.

4.1 LBNL, Principal Investigator and Science Team

The Principal Investigator (PI) at LBNL is responsible to DOE, and NSF for the total mission including the instrument, spacecraft, ground segment, mission planning and operations, data analysis, and data distribution. The science team is responsible for science validation and calibration, algorithm development, and the accuracy and production of all data products. The main web page for the SNAP mission is maintained at LBNL at URL, http://snap.lbl.gov.

The LBNL Physics Division, is host to the Supernova Cosmology Project (http://www-supernova.lbl.gov).

Data received by the Space Sciences Mission Operations Center will be sent directly to the adjacent DOE National Energy Research Scientific Computing Center (NERSC) located at LBNL. Data can then be immediately processed for identification of new supernovae and new operational commands can be quickly returned to the satellite. The NERSC facility is the largest non-classified computing center in the United States with an aggregate throughput of 3 teraflops (trillions of floating point operations per second). This capacity is about to be increased to 5.0 teraflops. Data would be available online from the High Performance Mass Storage System (HPSS) with a current capacity of 600 terabytes. More information about this facility can be found at URL, http://www.nersc.gov.

4.2 Space Sciences Laboratory

The Space Sciences Laboratory at the University of California, Berkeley will provide significant project management and systems engineering supporting the overall project. In addition, it is anticipated that the Mission & Science Operations Center, and the Berkeley Ground Station (11-meter dish) can be adapted for this mission. Both of these facilities are located at the Space Sciences Laboratory. Further information regarding these facilities can be found at URL, http://hessi.ssl.berkeley.edu/ground_systems. This system is installed with S-band but is X-band compatible.